Simulation of Drilling Process for Control of Burr Formation*

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Abstract

An analytical force model is presented to simulate the cutting force and the chip flow direction in the drilling process. Three dimensional chip flow is interpreted as a piling up of the orthogonal cuttings in the planes containing the cutting velocities and the chip flow velocities. The chip flow direction is determined to minimize the cutting energy. The simulation is performed to discuss the effect of the lip geometry on burr formation at the backside of the plate. Burr formation is associated with the thrust and the chip flow direction. The curved lips drill is examined to reduce the thrust and control the chip flow with the orientation and the curvature of the lips. The counterclockwise orientation with the small curvature is effective in reducing burr formation in the simulation. A drill is designed to have the counterclockwise curved shapes on the straight lips. The designed lips flow the chip upward to avoid the chip clogging in the steady process. Then, the curved shape at the end of the lips control the chip flow toward the radial direction of the tool to reduce burr formation with the thrust around the end of cut.

Key words: Drilling, Burr, Simulation, Cutting Force, Chip Flow

1. Introduction

Most of manufacturing industries perform a huge number of drilling operations in machine shops. The drilling technology has been studied to improve the cutting performance with optimizing the cutting parameters and the tool geometry. However, burrs are sometimes formed when the drill exits the workpiece and the exit burrs have to be removed in the deburring process. The control of burr formation, therefore, has been strongly required to reduce the post process of the drilling operation. Many researches have been made on burr formation and deburring so far. The earlier works associated the burr shape with the cutting parameters experimentally. Some mathematical models based on the experiments were presented to determine the cutting parameters⁽¹⁾. Burr control charts were also proposed to optimize the cutting parameters with taking into account burr formation⁽²⁾⁽³⁾. A statistical analysis was presented to estimate the burr height in the drilling process⁽⁴⁾. Burr formation was discussed with the microstructure of the material in micro-scale drilling⁽⁵⁾. Some of researches tried to associate the drill geometries with burr formations. A drill shape, in which the chisel edge was removed and the wedge angle and the web thickness were increased, was designed to suppress burr formation and evaluated for cuttings of some materials⁽⁶⁾. Step drills were used to reduce the exit burrs⁽⁷⁾. Because burr formation originally depends on stress and strain in the material to be cut, deformation of the material at the end of the cut has been analyzed in the finite element method. The FE analysis is effective in understanding the material behavior in the process⁽⁸⁾⁽⁹⁾⁽¹⁰⁾. However, it has not yet been applied to design of the drill geometry because it takes a long time for the

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simulations. Other analytical models, therefore, are required to optimize the geometry in the simulation.

From the point of view of the cutting force, the thrust at the end of the cut promotes burr formation in drilling of the plates. When the chip flows upward, a large burr is left at the edge of the hole. Therefore, the thrust and the chip flow direction should be controlled to reduce burr formation. This study focuses on the cutting force and the chip flow at the exit of the drill from the workpiece. An analytical model based on the minimum cutting energy is applied to prediction of the cutting process. Many force models in drilling have also been presented as well as those of the milling one so far ⁽¹¹⁾⁽¹²⁾. A model based on the minimum cutting energy was proposed to predict the cutting force with the chip flow direction in turning ⁽¹³⁾ and was applied to the drilling processes ⁽¹⁴⁾. However, the transient processes at the penetration and the exit of the tool in drilling have not yet been analyzed in the model. In order to reduce burr formation at the backside of the machined plate, the presented model simulates the thrust with the chip flow direction in the transient cutting process when the drilling tool exits the workpiece. Then, the lip geometry of the twist drill is discussed to reduce burr formation with the cutting force and the chip flow direction. Several curved lip shapes have recently been used in the machine shops of the automobile industry. The paper discusses the effect of the lip orientation and the curvature on the cutting process at the end of the cut using the simulation. A drill shape is designed to reduce burr formation with a large radial rake angle based on the simulation.

2. Simulation model in drilling process

An analysis model is applied to prediction of the cutting force with the chip flow direction in the drilling process. The chip flow is interpreted as a piling up of the orthogonal cuttings in the planes containing the cutting velocities and the chip flow velocities, as shown in Fig. 1. The cutting edges are divided into small discrete segments to make the orthogonal cutting models using the following data:

$$\left. \begin{aligned} \phi &= f(V, t_1, \alpha) \\ \tau_s &= g(V, t_1, \alpha) \\ \beta &= h(V, t_1, \alpha) \end{aligned} \right\} \quad (1)$$

where ϕ , τ_s and β are the shear angle, the shear stress on the shear plane and the friction angle. V , t_1 and α are the cutting velocity, the uncut chip thickness and the rake angle. Equation (1) can be obtained in the orthogonal cutting tests.

Because the cutting velocity V is the resultant of the circumferential velocity and the feed rate f , V is given by:

$$V = \sqrt{(R_p \omega)^2 + f^2} \quad (2)$$

Fig. 1 Chip flow model in drilling process

Fig. 2 Cutting force components

where ω and R_p are the angular velocity and the radius at a position P on an edge. Because the cutting direction is inclined at an angle of $\tan^{-1}(f/R_p\omega)$, the axial rake angle during cutting is regarded as $\alpha'_A = \alpha_A + \tan^{-1}(f/R_p\omega)$, where α_A is the nominal axial rake angle given by the tool geometry. When a chip flow angle η_c on the rake face is assumed, the orthogonal cutting model can be made by Eq. (1) with calculating the effective rake angle α_e .

Figure 2 shows an orthogonal cutting plane containing the cutting velocity V and the chip flow velocity V_c at an edge point P. X' - Y' - Z' is the coordinate system rotating with the cutting edge at the angular velocity ω , where X' -axis is in collinear with the cutter radius. Because the shear stress on the shear plane τ_s is given by Eq. (1), the shear energy in a segmented area dU_s is:

$$dU_s = \tau_s l_s dL_s \frac{\cos \alpha_e}{\cos(\phi_e - \alpha_e)} V \quad (3)$$

where l_s and dL_s are the length and the width of the shear plane on the segmented area. The friction energy dU_f is given by the friction force dF_f and the chip flow velocity V_c :

$$dU_f = dF_f V_c \quad (4)$$

where dF_f is given in the orthogonal cutting model as follows:

$$dF_f = \tau_s t_1 \frac{\sin \beta}{\cos(\phi_e + \beta - \alpha_e) \sin \phi_e} dL_f \quad (5)$$

where dL_f is the width of the tool chip contact area in the segmented edge. The chip flow velocity at the center of the cutting area removing material is given by:

$$V_c = \frac{\sin \phi_e}{\cos(\phi_e - \alpha_e)} V \quad (6)$$

The chip flow velocities in the other segmented areas on the cutting edge are calculated geometrically so that the chip flows the same direction and curls at the same angular velocity without plastic deformation in the chip. The cutting energy U , then, is given by integrating over the height $[h_{min}, h_{max}]$ of the cutting area as follows:

$$U = \int_{h_{min}}^{h_{max}} (dU_s + dU_f) dh \quad (7)$$

The chip flow angle η_c can be determined to minimize U in the iterative calculation. The cutting force, then, is predicted in the model at the minimum cutting energy.

The tangential cutting force in the segmented area dF_H is:

$$dF_H = (dU_s + dU_f) / V \quad (8)$$

The normal force on the rake face dF_n is given by:

$$dF_n = \frac{dF_H - dF_t \sin \alpha_e}{\cos \alpha_b \cos \alpha_R} \quad (9)$$

where dF_t is the friction force given by Eq. (5). α_R is the radial rake angle of the edge

Fig. 3 Chip formation in drilling process

Fig. 4 Twist drill

viewed from the inclined direction at an angle of $\tan^{-1}(f/R_p \omega)$; and α_b is the inclination angle of the rake face with respect to Z-axis direction in the plane that is perpendicular to the rake face. The radial component dF_T and the axial one dF_V are given by:

$$\left. \begin{aligned} dF_T &= -dF_t \cos \alpha_e \sin \eta'_c + dF_n \cos \alpha_b \sin \alpha_R \\ dF_V &= dF_t \cos \alpha_e \cos \eta'_c - dF_n \sin \alpha_b \end{aligned} \right\} \quad (10)$$

η'_c is the projected angle of the chip flow direction onto the vertical plane. dF_H , dF_T , and dF_V is converted into the components of X-, Y-, and Z- axis.

The chip formations on a chisel and a lip were observed in the cutting experiments. Figure 3 shows a picture of the chips at the interruption of cutting. The picture proves that the chip is formed on the chisel as well as the lip. However, the chip formation on the chisel is different from that of the lip. Therefore, the chip flow models are made on the chisel and the lip independently to calculate the cutting forces with the chip flow directions. The thrust is the sum of Z component of the cutting forces loaded on all cutting edges. The torque can be given by integrating over the radius $[R_{min}, R_{max}]$ of the cutting area as follows:

$$T = \int_{R_{min}}^{R_{max}} r \cdot dF_H dr \quad (11)$$

3. Cutting simulation of drilling processes

3.1 Definition of tool geometry

The general geometry of twist drills is defined as shown in Fig. 4. The twist drill consists of the chisel and the lips. The paper discusses the cutting process of a drill with a X type thinning, which inclines at an angle of 0 deg in the axial direction. Because burr formation strongly depends on the cutting process of the lips, the lip geometry is discussed with not only the straight edge but also the curved one. Table 1 shows the tool geometries examined in the simulation with the edge shapes viewed from the bottom of the tools,

Table 1 Tool geometry

Diameter	10 mm
Web inclination	140 deg
Web size	1.52 mm
Wedge angle	118 deg
Helix angle	30 deg
Relief angle	10 deg
Web center inclination	115 deg
Web center thickness	0.2 mm
Thinning	X type
Axial inclination angle at thinning	0 deg

Lip geometry

Fig. 5 Simulation of drilling process

Cutting conditions: material cut, aluminum alloy ADC12; tool, coated HSS; spindle speed, 640 rpm; feed rate, 110 m/min; lubrication, dry.

where the lines show the cutting edges. The curved lip shapes are curved clockwise or counterclockwise.

3.2 Case study

The simulation was performed to predict the cutting force of aluminum alloy ADC12 with the straight lip drill at a spindle speed of 640 rpm and a feed rate of 110 m/min. The following data was used in the simulation:

$$\left. \begin{aligned} \phi &= 0.07312V + 696.36t_1 + 1.7257\alpha - 2.3323 \\ \tau_s &= -5.6760V + 1001.0t_1 + 0.05902\alpha + 19.857 \\ \beta &= -2.2299V_1 + 0.34452\alpha - 0.04315 \end{aligned} \right\} \quad (12)$$

Figure 5 shows the changes in the thrust and the torque with the cutting time. The process consists of the following steps according to the cutting position:

- (1) The chisel penetrates into the material. The cutting area on the chisel increases with the cutter feed (Process O-A).
- (2) The chisel and the lips remove the material. The cutting areas on the lips increase with the cutter feed (Process A-B).
- (3) The chisel and the lips remove the material in the steady cutting process, where the

Fig. 6 Transient cutting process

Fig. 7 Radial rake angle

cutting areas do not change (Process B-C).

- (4) The chisel exits the material. The cutting area on the chisel decreases with the cutter feed (Process C-D).
- (5) The lips exit the material. The cutting areas on the lips decrease with the cutter feed (Process D-E).

The thrust and the torque change with the depth of the cutting position according to the above steps in the simulation. The cutting force increases rapidly at the chisel penetration; and increases gradually during the lips penetration. The cutting force does not change when the chisel and the lips remove the material simultaneously. The cutting force drops suddenly just after the exit of the chisel from the material; and then decreases gradually with the cutter feed.

Figure 6 shows the change in the cutting force in the transient process, where the cutting edges enter and exit the workpiece. The cutting process can be simulated well not only in the steady process but also in the transient process. The simulation of the cutting force can be verified in Fig. 5 and Fig. 6. The thrust and the torque are determined by the predicted chip flow angle at the minimum cutting energy. Because the simulated cutting force agrees with the measured one, the chip flow is estimated to incline at the simulated angle here.

3.3 Effect of lip curvature on burr formation

The cutting processes of the curved lips drills, which are shown in Table 1, were simulated to compare with the straight lips drill. Figure 7 shows the change in the radial rake angles with the rotational radius of the cutter, which can be derived from the shape of the grinding stone in manufacturing of the drills. Because the web inclination angle is larger than the web center inclination angle as shown in Table 1, the rake angle in the thinning area is negative. The cutting points of the outer edges in the clockwise curved drill delay with respect to the inner edge. Therefore, the radial rake angle of the lips is negative. The rake angle of the outer edge in the counterclockwise curved shape is positive because of the advanced cutting points. Figure 8 compares the simulated thrusts and the torques of the

Fig. 8 Effect of lips curve on cutting force

Fig. 9 Change in cutting force at the end of the cut

Fig. 10 Chip flow direction

curved lips drills with those of the straight one. The cutting force of the clockwise curved drill is almost same as that of the straight one. The cutting force of the counterclockwise curved lips, meanwhile, is slightly smaller than those of the straight and the clockwise curved drills.

Figure 9 compares the thrusts around the end of the cut, where the drill exits the workpiece. The thrust of the counterclockwise curved drill is smallest in the examined tools. The counterclockwise curved lips, therefore, is expected to reduce burr formation. Figure 10 shows the chip flow angles at the end of the lips. The ends of the lips start cutting at 1.5 sec after the chisel enters workpiece. The large chip flow angle means that the chip flows toward the radial direction of the tool. The chip flow angle of the counterclockwise curved and the straight drills increases after the chisel exits the workpiece. The chip flow angle of the counterclockwise curved drill is larger than the angle of the straight lips because of large radial rake angles of the ends of the lips. Meanwhile, the small chip flow angle continues in the cutting process with the clockwise curved drill because of the negative rake angles.

Figure 11 shows the thrust and the chip flow angle with the curvature of the lips when the ends of the lips remove the material at 0.54 mm before the end face of the plate. The thrust and the chip flow angle of the clockwise curved shape do not change largely with the curvature. The chip flow angle decreases with the curvature because of the large negative

Fig. 11 Effect of curvature of lips

Fig. 12 Designed tool

Fig. 13 Radial rake angle

Fig. 14 Cutting force of designed tool

radial rake angle. The effect of the axial rake angle on the cutting force becomes large when the chip flows upward. Therefore, the thrust reduces a little because of the positive axial rake angle. Meanwhile, the smaller curvature of the counterclockwise curved shape flows the chip toward the radial direction at the larger chip flow angle. Then, the thrust reduces with the axial component of the chip flow velocity. The counterclockwise curved drill is expected to reduce burr formation with changing the chip flow direction and reducing the thrust.

3.4 Design of a curved lip drill

Because the counterclockwise curved lips with the small curvature are effective in reducing the thrust and controlling the chip flow, a drill was designed to reduce burr formation. Figure 12 shows the designed tool viewed from the bottom of the tool. The tool has the counterclockwise curved shapes on the straight lips. The small curvature 3 mm is formed from $X = 1.2$ mm to the ends of the lips with keeping the strength of the tool, where the straight lips are left from the end of the thinning to $X = 1.2$ mm. Figure 13 shows the radial rake angle with the rotational radius of the cutter. The radial rake angle at the end of the lip is 30.5 deg, which is much larger than a radial rake angle of 19.2 deg in the

Fig. 15 Chip flow angle of designed tool

counterclockwise curved shape shown in Table 1. Figure 14 compares the cutting force of the designed tool with the counterclockwise curved shape. The cutting force of the designed tool does not change remarkably. However, the thrust is reduced to 3.31 N when the ends of the lips remove the material at 0.54 mm before the end face of the plate. Figure 15 compares the chip flow angle of designed tool with that of the counterclockwise curved drill. The designed tool flows the chip upward to avoid the chip clogging in the steady process at small chip flow angles. Then, the chip flow angle increases remarkably to reduce burr formation with the thrust around the end of cut.

The result in Fig. 15 is discussed in an analysis without the experimental verification. Therefore, further studies should be required to quantify the effect of the designed geometry. However, the simulation presented in this paper gives a direction to reduce burr formation. From the point of burr reduction, the chip flow is recommended to incline toward the radial direction of the tool. The results of the simulation show that a large radial rake angle at the ends of the lips could control the chip flow to reduce the burr formation.

4. Conclusion

An analytical simulation was presented to discuss the lip shape of the twist drill with taking into account burr formation. The force model based on the minimum cutting energy was verified in a cutting test. The simulated cutting force agreed with the measured one not only in the steady process but also in the transient process.

Because burr formation occurs on the backside of the machined plate, this study focuses on the cutting process around the end of the cut. Burr formation is associated with the thrust and the chip flow angle. The small thrust with the chip flow toward the radial direction of the tool can be expected to reduce burr formation. The simulations were performed with changing the orientation and the curvature of the curved lips drills. The thrust at the end of the cut reduces and the chip flows toward the radial direction of tool in cutting with the counterclockwise curved drill. The smaller curvature, then, is expected to be more effective in reducing burr formation. A drill is designed to control the chip flow with combining the straight and the curved lips. The designed lips flow the chip upward to avoid the chip clogging in the steady process at small chip flow angles. Then, the curved lips control the chip flow toward the radial direction to reduce burr formation with the thrust around the end of cut. Although the tool design in this paper is based on the simulation without the experimental verification, the presented simulation gives a direction of the tool design.

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